# Physical and Mechanical Properties of Geopolymer Mortars Produced with Different Bacterial Strains within a Circular Economy Framework

Mücteba Uysal[1], Orhan Canpolat[1](✉), Nihal Doğruöz Güngör[2], Elif Özlem Arslan Aydoğdu[2], Harun Tanyıldızı[3], Mahmut Sezer[4], Aygül Zara Kebir[1], Abdulaziz M. O. Alhaddad[1], Huzeyfe Ömer Abdüsselamoğlu[1], and Youssef Alkhabaze[1]

[1] Yildiz Technical University, Istanbul 34220, Türkiye
canpolat@yildiz.edu.tr
[2] Istanbul University, Istanbul 34134, Türkiye
eoarslan@istanbul.edu.tr
[3] Firat University, Elazig 23119, Türkiye
[4] Istanbul Aydin University, Istanbul 34295, Türkiye

**Abstract.** This study investigates the physical and mechanical performance of metakaolin–slag-based geopolymer mortars containing ureolytic bacteria, such as *Sporosarcina pasteurii*, and cave-derived bacteria, including *Bacillus safensis* and *Micrococcus aloeverae*, with a view toward exploring their self-healing potential. The incorporation of microbial healing in geopolymer systems aligns with circular economy principles by valorizing industrial by-products, enhancing material durability, and reducing the need for resource-intensive repairs. While laboratory strains like *Sporosarcina pasteurii* are well-known for their high urease activity and alkaline tolerance, cave-isolated strains offer distinct advantages due to their natural adaptation to high-alkalinity and nutrient-poor geological environments, providing resilient and highly compatible ureolytic alternatives. The formation of natural cave structures, including stalactites, stalagmites, cave pearls, and flowstones, demonstrates the efficacy of microbially induced carbonate precipitation for sustainable concrete repair. In this study, the workability, physical properties (water absorption, open porosity, bulk density, ultrasonic pulse velocity, shrinkage), and mechanical properties (compressive and flexural strength) of the mortars were evaluated. The results are expected to introduce novel cave-derived microbial species to the literature and promote the use of environmentally sustainable, self-healing construction materials that contribute to a circular and resource-efficient building sector.

**Keywords:** Geopolymer · Metakaolin–Slag-Based Geopolymer Mortar · *Bacillus safensis* · *Micrococcus aloeverae* · Sustainable Construction Materials · Circular Economy

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## 1 Introduction

The global construction industry faces the dual challenge of increasing infrastructure demand and the need for environmental sustainability. Traditional cement production contributes approximately 5% of global $CO_2$ emissions, motivating the search for eco-friendly alternatives [1]. Geopolymers, introduced by Davidovits in 1978, are alkali-activated aluminosilicate materials formed from industrial by-products such as fly ash and slag or processed natural materials like metakaolin. These materials develop a three-dimensional Si–O–Al–O network, offering enhanced mechanical performance, durability, and a lower carbon footprint compared to ordinary Portland cement [2, 3].

Despite these advantages, geopolymer composites are susceptible to crack formation, which compromises durability by increasing permeability and allowing the ingress of aggressive agents. While conventional repair methods can address larger cracks, micro-cracks ($< 0.3$ mm) remain challenging to treat, highlighting the need for innovative self-healing strategies [4–7].

Microbially induced carbonate precipitation (MICP) offers a promising autonomous healing mechanism. In this process, microorganisms precipitate calcium carbonate ($CaCO_3$) within cracks, sealing them and reducing permeability. Although *Sporosarcina pasteurii* exhibits high alkaline tolerance, standard laboratory strains may encounter physiological limitations in geopolymers, prompting the use of resilient cave-isolated strains adapted to extreme geological environments [6, 8, 9].

Cave environments are natural analogs for $CaCO_3$ precipitation, producing speleothems like stalactites and stalagmites. Microorganisms from these environments are hypothesized to offer superior survival and biomineralization capabilities within geopolymer matrices. Integrating these cave-derived bacteria with metakaolin–slag-based geopolymers provides a novel approach to enhancing mechanical performance, durability, and autogenous self-healing, while promoting environmentally sustainable construction [10].

Cave-derived bacterial isolates used in this study were obtained from soil and surface samples collected during fieldwork carried out at Yarık Sinkhole (Antalya, Türkiye). Prior to this study, these isolates had been screened for their biomineralization and carbonate precipitation potential under laboratory conditions.

This study evaluates the fresh and hardened properties of geopolymer mortars incorporating three bacterial strains—*S. pasteurii, Bacillus safensis,* and *Micrococcus aloeverae*. Their survival in the highly alkaline geopolymer environment and their ability to induce MICP were assessed. The findings aim to identify the most suitable bacterial strains for sustainable crack-healing applications and to expand knowledge on cave-derived microorganisms for eco-friendly, self-healing construction materials. Previous studies have shown that these cave-derived isolates exhibit carbonate precipitation and biomineralization activity in B4 calcification medium. These findings suggest that these bacteria could be suitable candidates for self-healing geopolymer applications. The performance of the selected strains is planned to be compared, and their crack-healing potential will be experimentally verified, particularly for *Micrococcus aloeverae*, whose MICP activity is less documented in the literature.

## 2 Materials and Methods

### 2.1 Materials

The main pozzolanic binder in the geopolymer was metakaolin with high pozzolanic activity ($SiO_2 + Al_2O_3 > 85\%$) and a specific gravity of 2.52 g/cm$^3$, conforming to ASTM C618, Class N, with a Blaine fineness of 20 000 cm$^2$/g [11, 12]. Ground granulated blast furnace slag (GGBFS) was also used as a pozzolan, with a specific gravity of 2.91 g/cm$^3$, conforming to ASTM C989, Class R, and a Blaine >2750 cm$^2$/g [13, 14]. The high Blaine values of both materials indicate fine particle sizes, promoting rapid reaction and early strength development. As the alkaline reactant mixture a combination of laboratory-prepared sodium hydroxide (NaOH) solution and commercially available sodium silicate ($Na_2SiO_3$) solution was used. The NaOH solution was prepared 24 h prior to mortar production at a concentration of 12 M by dissolving 99.0% purity NaOH pellets [15] in distilled water [16], considering the molar mass of NaOH as 40 g/mol. The 40% sodium silicate solution [17] had a $SiO_2/Na_2O$ molar ratio of 2.70 and a density of 1.37 g/cm$^3$.

In the geopolymer mortars, river sand was used as the aggregate, with a maximum particle size of 2.0 mm [18]. Polyvinyl alcohol (PVA) fibers (density: 1.1 g/cm$^3$) were incorporated at 0.60% by volume into all mixtures to enhance ductility and crack-bridging performance.

The bacterial strains used in this study were the reference ureolytic strain *Sporosarcina pasteurii* (SP) and two cave-derived isolates, *Bacillus safensis* (Y109) and *Micrococcus aloeverae* (Y147). The Y109 and Y147 strains used in this study were previously isolated from Yarık Düdeni in Antalya. Isolation was achieved using culture-based microbiological methods from soil and surface samples during cave exploration expeditions. The obtained isolates were purified and identified by 16S rRNA gene sequencing. These strains were selected based on prior screening studies demonstrating their carbonate precipitation and biomineralization activity on B4 calcification medium, which suggested their potential suitability for self-healing geopolymer applications. Before impregnation, bacterial suspensions were adjusted to McFarland 3 turbidity standard (approximately $9 \times 10^8$ CFU/mL) so that all series were prepared at a comparable cell density. To ensure a reliable comparison, all three strains were evaluated based on their ureolytic activity; therefore, suspensions were prepared in B4 medium supplemented with urea to support and trigger urease-mediated carbonate precipitation, rather than standard PBS. GGBFS was used as the bacterial carrier material in the impregnation process.

### 2.2 Methods

Initially, preliminary experimental studies were conducted to determine the most suitable solid binder system. Geopolymer mortars based on 100% GGBFS, 75% GGBFS + 25% metakaolin, and 25% GGBFS +75% metakaolin were produced and mechanically evaluated. The mortar series exhibiting the highest performance was selected for further investigation. For the selected mortar series, fresh geopolymer samples were examined in terms of workability [20], while their physical properties, including water absorption,

open porosity, and bulk density [21], ultrasonic pulse velocity [22], and shrinkage [23], as well as their mechanical properties, namely compressive strength [24] and flexural strength [25], were evaluated. The specimens used for testing were cured at ambient temperature (20 ± 2 °C).

The bacterial impregnation procedure was adapted from Ziada (2022) [19], with GGBFS substituted as the carrier material. Isolate selection was based on prior screening studies in which both strains demonstrated crystal formation and carbonate-precipitation activity on the B4 calcification medium. Bacterial cells were weighed into centrifuge tubes and suspended in B4. The resulting suspension was then mixed with GGBFS to initiate bacterial immobilization onto the slag surface. The mixture was incubated at 30 °C for 24 h, after which it was filtered to yield a bacterial-impregnated GGBFS paste. To reduce excess moisture, the paste was oven-dried at 30 °C for 40 min prior to use. For experiments evaluating physical and mechanical properties, 9.9 mL of bacterial suspension, 47 mL of B4 solution, and 44 g of slag were used in the impregnation process.

## 3 Results and Discussion

### 3.1 Preliminary Findings

Initially, fiber selection was carried out using 100% slag-based geopolymer mortars. Within this scope, carbon fibers, basalt fibers, and PVA fibers were tested at volume fractions of 0.4%, 0.6%, and 0.8%. Based on the workability (flow table test) and flexural tensile strength results, a PVA fiber content of 0.6% was selected for further experiments. Subsequently, partial replacement of slag with metakaolin was applied to obtain more balanced geopolymer composites. In GGBFS-based geopolymer systems, rapid reaction kinetics may lead to variations in workability and microstructural development due to the high reactivity of slag. In contrast, metakaolin provides a more controlled aluminosilicate source, contributing to a more stable geopolymerization process and improved microstructural homogeneity. Therefore, GGBFS–metakaolin-based systems are expected to exhibit more consistent and reproducible performance. Based on preliminary screening results, the mixture containing 25% GGBFS and 75% metakaolin (Mix 3), which exhibited the highest 1-day compressive strength (46.6 MPa) among the tested mixtures (Mix 1: 23.8 MPa; Mix 2: 29.4 MPa), was selected as the primary binder composition for the main experimental program (Table 1). The compressive strength results were obtained from three 5 cm cube specimens prepared for each mixture. Prior to testing, the specimens were subjected to oven curing at 80 °C for 24 h.

**Table 1.** Components and strengths of geopolymer mortars (for 375 $cm^3$ specimens).

| Mix ID | Components (g) | | | | | |
|---|---|---|---|---|---|---|
| | GGBFS | Metakaolin | NaOH | $Na_2SiO_3$ | Sand | PVA |
| Mix 1 | 200 | 0 | 61.3 | 122.7 | 500 | 2.5 |
| Mix 2 | 150 | 50 | 61.3 | 122.7 | 500 | 2.5 |

(*continued*)

**Table 1.** (*continued*)

| Mix ID | Components (g) | | | | | |
|---|---|---|---|---|---|---|
| | GGBFS | Metakaolin | NaOH | $Na_2SiO_3$ | Sand | PVA |
| Mix 3 | 50 | 150 | 61.3 | 122.7 | 500 | 2.5 |

### 3.2 Main Experiments

Table 2 presents the design of the investigated mixtures, including mix proportions and bacterial incorporation details.

**Table 2.** Mix design and bacterial incorporation details (for 1499.3 $cm^3$ specimens).

| Series ID | Bacterial type | Components (g) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | GGBFS | Bio-GGBFS | Metakaolin | NaOH | $Na_2SiO_3$ | Sand | PVA |
| GP-SP | SP | 156 | 44 | 600 | 245.3 | 490.7 | 2000 | 9.9 |
| GP-Y109 | Y109 | 156 | 44 | 600 | 245.3 | 490.7 | 2000 | 9.9 |
| GP-Y147 | Y147 | 156 | 44 | 600 | 245.3 | 490.7 | 2000 | 9.9 |

According to the flow table test results, the highest flow value was obtained for the GP-Y147 series (132.3 mm), followed by the GP-Y109 (125.3 mm) and GP-SP (119.3 mm) series. This suggests that different bacterial strains may have a slight influence on workability.

Figure 1 shows the appearance of the geopolymer mortar specimens produced within the scope of this study immediately after being cast into molds.



**Fig. 1.** Geopolymer mortar specimens produced within the scope of this study.

The geopolymer mortars showed minor variations in water absorption (11.3–11.7%), open porosity (21.4–22.1%), and bulk density (1.88–1.89 g/$cm^3$) across the bacterial series, indicating a negligible effect of bacterial strains on their physical properties.

The UPV test results obtained on 28-day-old geopolymer mortar specimens showed slight variations among the different bacterial series. The UPV values ranged from 3284 m/s to 3400 m/s. The highest UPV value was recorded for the GP-Y147 series (3400 m/s), followed by the GP-SP series (3371 m/s), while the lowest value was obtained for the Mix-Y109 series (3284 m/s). Overall, the results indicate that the incorporation

of different bacterial strains had a minor influence on the ultrasonic pulse velocity of the hardened geopolymer mortars.

Overall, a consistent relationship was observed between the physical properties (water absorption, open porosity, and bulk density) and the ultrasonic pulse velocity (UPV) results. The GP-Y147 series, which exhibited the lowest water absorption (11.3%) and open porosity (21.4%) together with the highest bulk density (~1.89 g/cm$^3$), correspondingly showed the highest UPV value (3400 m/s). In contrast, the Mix-Y109 series, which presented relatively higher porosity and water absorption values, exhibited the lowest UPV (3284 m/s), while the GP-SP series remained intermediate in all measured properties. These findings confirm that lower porosity and water absorption are associated with higher ultrasonic wave propagation velocity, indicating a coherent microstructure–wave transmission relationship in the hardened geopolymer mortars.

The differences observed among the bacterial series may reflect the distinct physiological and biomineralization characteristics of the tested strains. Earlier work on Yarık Sinkhole isolates has shown that these bacteria are capable of inducing carbonate precipitation under controlled laboratory conditions. Against this background, the higher mechanical performance of GP-SP and GP-Y109 is linked to favorable bacterial–matrix interactions. Although all strains exhibit ureolytic activity, their geopolymer performance differed. The lower strength in GP-Y147 is attributed to its non-spore-forming nature, as resistant *Sporosarcina* and *Bacillus* endospores withstand the high pH of geopolymerization, whereas non-spore-forming *Micrococcus* cells are more vulnerable to such harsh conditions, leading to reduced biomineralization within the matrix.

Shrinkage measurements were conducted for the GP-SP and GP-Y109 series. Considering the specific properties of geopolymer mortars, measurements were taken at days 1, 2, 3, 4, 5, 6, 7, 14, and 28. This sampling scheme allowed for a detailed assessment of both early-age and later-age shrinkage behavior. The results indicate that both GP-SP and GP-Y109 geopolymer mortar series exhibited progressive shrinkage with curing time. In general, shrinkage increased continuously up to 28 days for both mixtures, reaching final values of −2.3% for both GP-SP and GP-Y109, indicating similar long-term volumetric behavior. In the early curing stage (1–7 days), both series showed fluctuations in shrinkage development. GP-Y109 generally exhibited slightly higher shrinkage at very early ages, while GP-SP showed a more pronounced shrinkage development in the later early-age period. However, after 14 days, both mixtures demonstrated nearly identical shrinkage trends, suggesting that the influence of bacterial incorporation on deformation behavior is limited. Overall, the results indicate that both bacterial series exhibit similar drying and autogenous shrinkage behavior, with only minor differences between GP-SP and GP-Y109 throughout the curing period.

The compressive and flexural strength results of the 28-day-old geopolymer mortar specimens show a clear variation among the different bacterial series. The GP-SP series exhibited the highest compressive strength (52.5 MPa), followed closely by the GP-Y109 series (50.4 MPa), while the GP-Y147 series showed a noticeably lower compressive strength (37.0 MPa). This indicates that the bacterial strain has a more pronounced influence on compressive strength compared to flexural strength. In contrast, flexural strength values were relatively close to each other, ranging from 8.7 MPa to 9.1 MPa. The GP-SP series again showed the highest flexural strength (9.1 MPa), while the lowest

value was observed for the GP-Y147 series (8.7 MPa). Overall, the results suggest that bacterial incorporation has a limited effect on flexural performance, whereas compressive strength is more sensitive to the type of bacterial strain used, with GP-Y147 exhibiting a significantly lower structural performance compared to GP-SP and GP-Y109.

Across all tested properties, the geopolymer mortars demonstrated consistent performance regardless of bacterial incorporation. While physical properties remained largely unaffected, mechanical performance—particularly compressive strength—showed a strain-dependent response. Overall ranking of performance can be summarized as: GP-SP $\approx$ GP-Y109 $>$ GP-Y147 These results suggest that cave-derived bacterial strains such as *Bacillus safensis* and *Micrococcus aloeverae* can perform comparably to *S. pasteurii* in geopolymer systems. This supports their potential use as sustainable microbial agents in self-healing cementitious materials.

## 4 Conclusion

In this study, the fresh and hardened properties of metakaolin–slag-based geopolymer mortars incorporating *S. pasteurii* (SP), *Bacillus safensis* (Y109), and *Micrococcus aloeverae* (Y147) were investigated. All mixtures exhibited adequate workability and similar physical properties, including water absorption, open porosity, and bulk density, indicating a generally compact and homogeneous microstructure. Compressive strength was clearly influenced by bacterial strain, with GP-SP and GP-Y109 outperforming GP-Y147, while flexural strength showed only minor differences among the series. Overall, the performance ranking can be summarized as GP-SP $\approx$ GP-Y109 $>$ GP-Y147. These results demonstrate that cave-derived bacterial strains can perform comparably to conventional ureolytic bacteria in geopolymer mortars. The findings support the potential use of alternative biomineralization-positive microorganisms for sustainable, self-healing construction materials. Future work will focus on investigating the autogenous self-healing potential of metakaolin–slag-based geopolymer mortars activated via an injection-based bacterial delivery method.

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